5. Andre Simon : "Study of the relationship between turbulent fluxes in deeply stable PBL situations and cyclogenetic activity"

(results related to ALATNET topic achieved during the period between 01.02.2003 and 31.08.2003)

Description of experiments with dry and conditional symmetric instability in the ARPEGE / ALADIN model

Introduction

The experiences with simulation of the 20 December 1998 storm, as well as the outputs of diagnostics and adjoint sensitivity tests considerably modified the original concept of the study. It was written in the previous issues of the ALATNET newsletters [7] and [8], that the success of the current vertical diffusion scheme in forecasting deep cyclogenesis in Northern Atlantic was build upon unrealistic reduction of static stability in the upper PBL levels. This kind of parameterisation had apparently drawbacks in enhancement of false cyclogenesis and destruction of inversion without possibility of a reasonable compromise based on simple retuning of the scheme. Experiments with different physical parameterisations, including Mellor-Yamada second-order closure scheme for turbulent fluxes and Smith scheme for precipitation (described in [9]), proved that the matter of forecasting deep cyclogenesis can be related to different parts of model physics (e.g. to the parameterisation of stratiform precipitation). However, the evaluated physical parameterisations didn't give realistic results on the 20 December 1998 storm evolution. Although these experiments were necessary to understand the behaviour of the simulated storm, the relationship between stratiform precipitation or cloudiness parameterisation and cyclogenesis is already beyond the scope of the originally proposed topic.

Hence it was decided to find further ways how to develop the operational vertical diffusion scheme, that could be useful for more realistic forecasts of cyclogenesis.

Theoretical background

One of the possibilities, how to adjust the current scheme of the vertical diffusion, was to find an analogue to the parameterisation of slantwise (shear-linked) convective processes. It was shown that this kind of parameterisation, described in [2], has a strong impact on model cyclogenesis (both for the false and the realistic cases). Hence it was supposed that a counterpart in the scheme of turbulent transport is necessary to reach a physical equilibrium (strong slantwise motions should be accompanied by increased turbulence and exchange of physical properties on a slope). Further motivation to continue in this direction was the problem of the shear-linked convection scheme in destroying the forecast of the 20 December 1998 cyclone and some unwanted effects in tropical convection (exaggerated height of the tops of the clouds).

The idea, how to introduce the effects of slantwise motions into the currently pure vertical physical parameterisations of ARPEGE/ALADIN, followed the work of Bennets and Hoskins (see article [1]) about symmetric instability.

For a dry atmosphere, the satisfactory criterion for symmetric instability is to reach negative values of potential vorticity. One can easily express this condition in a 2d system, using the formula :

$$P = S^4 (F^2 N^2 / S^4 - 1) = S^4 (Ri' - 1) < 0 \qquad (1)$$

where : $F^2 = f(f + \partial v/\partial x)$, $N^2 = g/\theta_0 (\partial\theta/\partial z)$, $S^2 = f(\partial v/\partial z) = g/\theta_0 (\partial\theta/\partial x)$

Hence F^2 represents the absolute vorticity of a 2d system, N^2 is the square of the Brunt-Väisälä frequency and the term S^2 contains the vertical wind-shear linked to the horizontal gradient of temperature through the "thermal wind" equation.

Consequently, the modified Richardson number *Ri'* represents the ratio between the slopes of "absolute momentum" and "potential temperature" surfaces [4]. Hence the dry-symmetric instability appears when the slope of the "potential temperature" surfaces exceeds the slope of the "absolute momentum" surfaces.

In the parameterisation we expect that similar relationships as in the 2d case can be used also for the 3d model. This is done in a simplified way by replacing the absolute vorticity and the wind-shear of the 2d systems by anological fields in 3 dimensions. Further we invert the relationship (1), saying that if dry-symmetric instability appears, the modified Richardson number will reach the neutrality in the turbulent scheme. Thus we come from the originally used Richardson number *Ri* to the modified one, named Ri_p, following the relationship :

$$Ri_p = Ri' - 1 = (\zeta / f)\, Ri - 1 \tag{2}$$

For the surface fluxes, the way of introducing the symmetric instability is more difficult, because we don't know and we basically cannot neglect the surface values of vorticity. Hence we estimate them by a very simple power-extension formula :

$$\xi_s = \xi_{ref} (z_s / z_{ref})^{\alpha}, \qquad \xi = \zeta - f \tag{3}$$

where the power is dependent on the stability between the surface and the reference lowest model level.

We can get a similar relationship as (1) for the conditional symmetric instability in a moist atmosphere. The satisfactory condition for the instability is the negative value of the moist potential vorticity, where the square of the Brunt-Väisälä frequency (N^2) in (1) is replaced by the square of the "moist" Brunt-Väisälä frequency (N_w^2). The computation of the moist Brunt-Väisälä frequency follows the expression proposed by Durran and Klemp in [3], that is already used for the parameterisation of the shear-linked convection.

The formula used for the parameterisation of the Richardson number modified by conditional symmetric instability after some approximations yields :

$$Ri_p = (N_w^2 / N^2)\, (\zeta / f)\, Ri - 1 \tag{4}$$

The surface fluxes are treated in a similar way as in the case of the dry-symmetric instability. However, realistic diagnostics of conditional symmetric instability is a much more difficult task, as it was shown in the experiments of Bennets and Hoskins in [1]. The intensity of the slanted ascent (descent) should be dependent on such parameters as the depth of the atmosphere or the width of the updraught.

First tests with the parameterisation of the dry symmetric instability showed difficulties, when the equation (2) was applied for negative Richardson numbers. Hence the further tasks split in two parts:

a) application of the Richardson number modification only by stable stratification, where dry (conditional) symmetric instability appears,

b) different modification of the Richardson number, with indirect dependency on dry (conditional) symmetric instability represented by the Ri_p number. This dependency is separated in two formulas, with respect to the type of stratification (stable, unstable) and curvature of the flow (cyclonic, anticyclonic). The scheme gives a linear dependency of the modified Richardson number Ri^* on the original one, with the possibility of tuning the slope of the $Ri^*(Ri)$ function.

Hence for the cyclonic case and for $Ri_p < 0$ the formula for Ri^* leads to :

$$Ri^* = \left[\left(1 + 1/a\,(1 + |\zeta / f|\,)^{-a}\right) / \,(1 + 1/a)\right] Ri \tag{5}$$

and for the anticyclonic case (and $Ri_p > 0$) we have :

$$Ri^* = \left[(1 + 1/a) \,/\, \left(1 + 1/a\,(1 + |\zeta / f|\,)^{-a}\right)\right] Ri \tag{6}$$

where "a" is a tunable parameter.

Thus we support turbulent transport in regions with dry or conditional symmetric instability in both cyclonic and anticyclonic environment and we suppress it for the anticyclonic case without presence of any instability.

Evaluation of the modified vertical diffusion

Parameterisation of the dry symmetric instability, conditional symmetric instability and conditional symmetric instability together with shear-linked convection was tested on several case studies. These included the cases with rapid cyclogenesis such as the cyclone of 20 December 1998 or the famous Christmas storms from 25 and 26 December of 1999. Besides, several cases of false mesoscale cyclogenesis in the ALADIN-France or ALADIN-LACE were evaluated.

A particular case was the simulation of the so-called "Balearic super-storm" event from November 2001, described in [6] on ALADIN-France. Forecasts of this situation by ARPEGE and ALADIN represented an intermediate between the false mesoscale cyclogenesis and the storms from December 1998 and 1999. A common characteristics for all situations is a strong baroclinic environment, where the cyclones develop very rapidly.

a

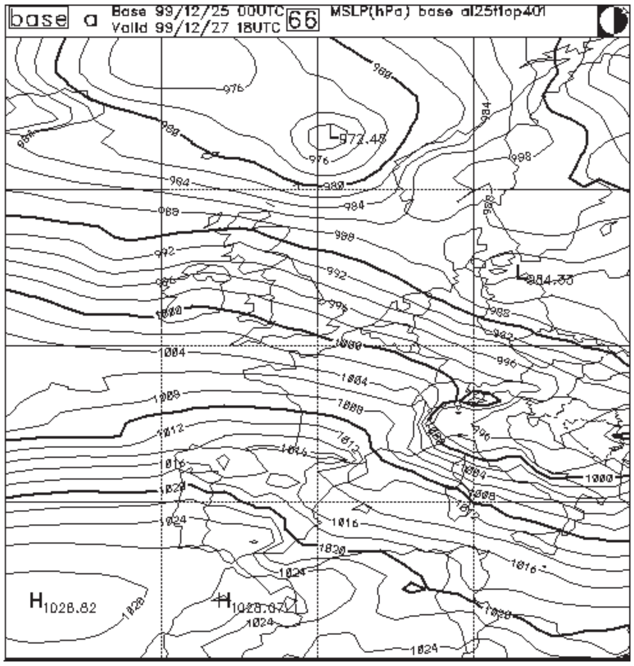


Figure 1a : 66-hour forecast of mean-sea-level pressure, based on 25.12.1999 00 UTC, in the reference ARPEGE run with the operational package of physical parameterisation (cycle 25T1_op4). Note the pattern of shallow trough towards West from the French coast.

b

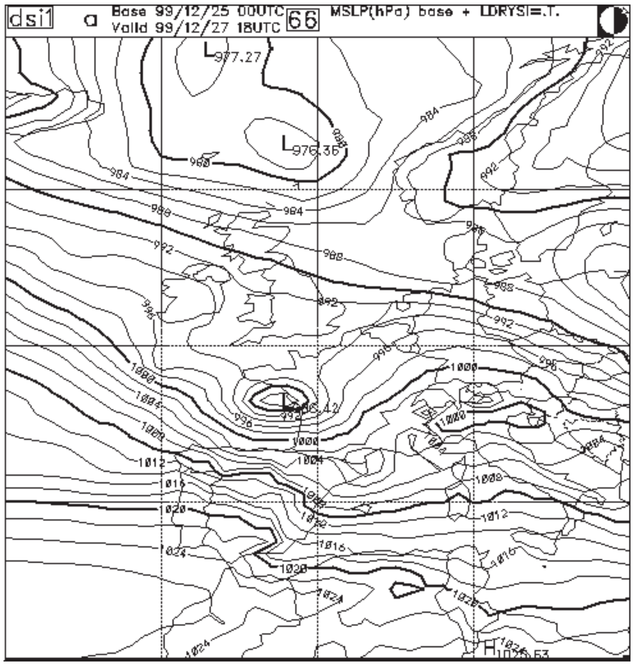


Figure 1b : The same as in Fig.1a but with activation of the parameterisation of dry symmetric instability inside the vertical diffusion scheme.

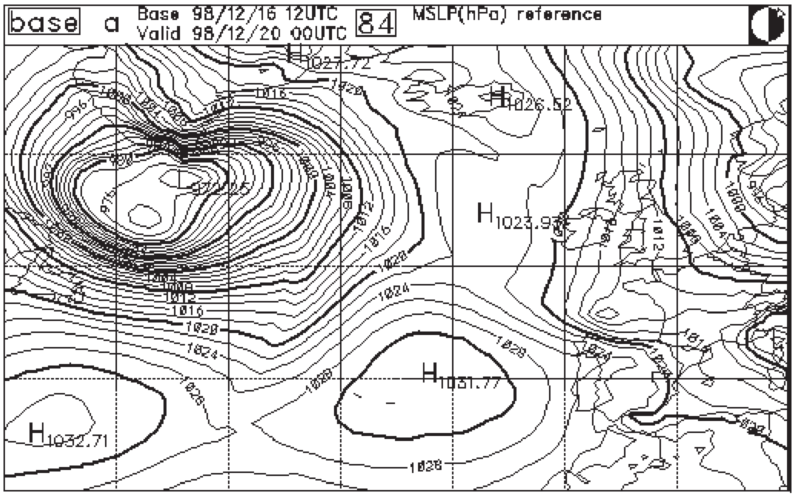


Figure 2a : 84-hour forecast of mean-sea-level pressure, based on 16.12.1998 12 UTC, in the reference ARPEGE run with the operational package of physical parameterisation (cycle 25T1_op4).

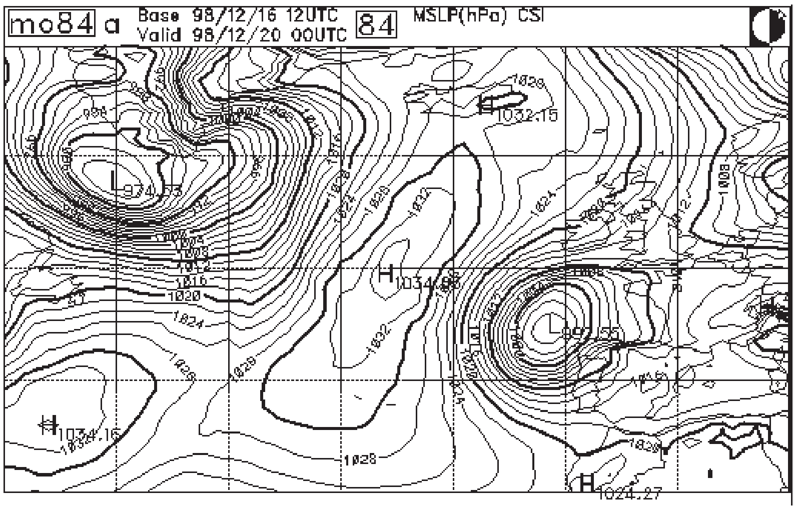


Figure 2b : The same as in Fig. 2a, but with activation of the Richardson number directly modified with respect to conditional symmetric instability.

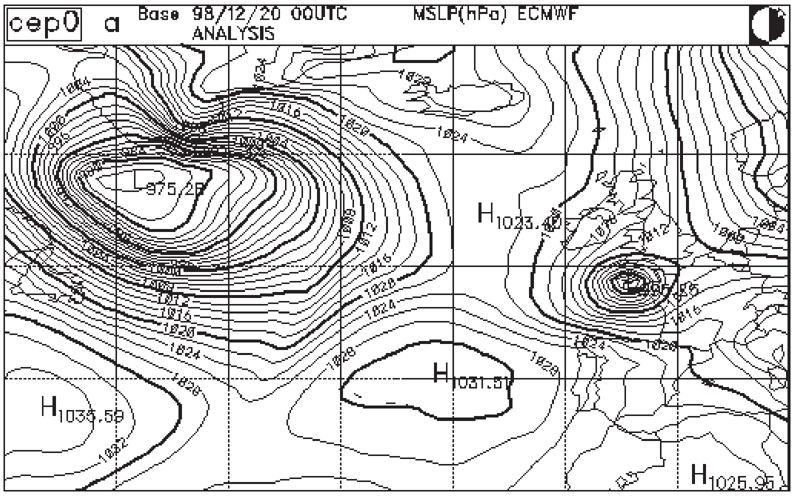


Figure 2c : Verifying model analysis valid at 20.12.1998 00 UTC

The direct application of the dry symmetric instability scheme after (2) had a very small impact on both 84- and 96-hour forecasts of the "20 December 1998" storm. On the other hand, one can see a strongly positive impact in the case of the second Christmas storm in the run from 25.12.1999 00 UTC (Fig. 1b). However, case studies on false cyclogenesis showed worse results for runs with this kind of parameterisation than for the reference model runs. The scheme was even able to trigger mesoscale cyclogenesis (e.g. in the case of false cyclogenesis from 2 May 2002).

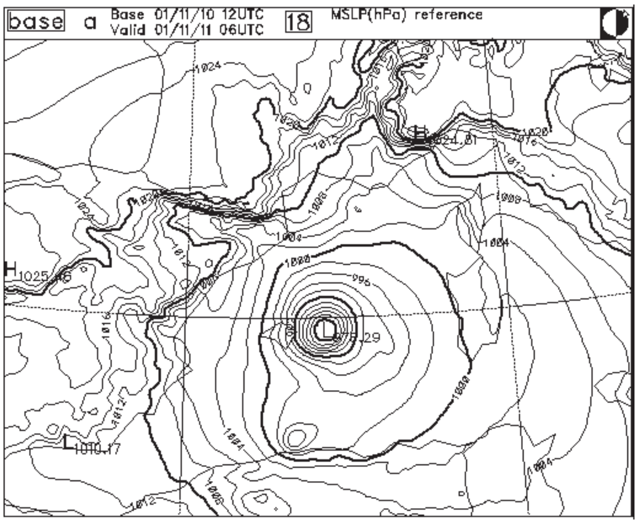
The scheme of the conditional symmetric instability (after formula 4) had a surprisingly big effect, above all in the case of the "20 December 1998" cyclogenesis (Fig. 2). In both 84- and 96-hour runs the storm was forecasted with the scheme, whereas the reference run predicted only a shallow low or trough. On the other hand, the position of the cyclone and the shape of the mean-sea-level pressure field are not corresponding to the model analysis valid at 20 December 1998 00 UTC. Looking at the development of the storm for the period 16 December 1998 - 20 December 1998, the forecasted cyclone was never in the dissipative stage in the first 66 hours of this period. Hence the development doesn't fit with the evolution based on the model analysis [8].

Experiments on further case studies showed mostly positive impact, in contrary to the scheme of dry symmetric instability. Moreover, the parameterisation of conditional symmetric instability keeps still better performances against the reference run in the case study of the second Christmas storm. In situations with false mesoscale cyclogenesis the modified vertical diffusion was able to cancel it (runs from 02.05.2002 00 UTC and 23.08.2002) or at least to be neutral (for the case of the so-called Adriatic storm of 20.07.2001).

The worst results of the evaluated turbulent diffusion scheme were obtained for the case study of the so-called "Balearic super-storm", above all in the run from 10.11.2001 12 UTC (Fig. 3). The scheme was not able to correct the extreme gradient of pressure near the centre of the cyclone, and the depth of the cyclone was even amplified.

Additional activation of the shear-linked convection improved most of the results obtained by experiments with dry or conditional symmetric instability. This positive impact is visible on the forecasts of the "20 December 1998" cyclone, where both the position and the shape of the mean-sea-level pressure field look more realistic.

a



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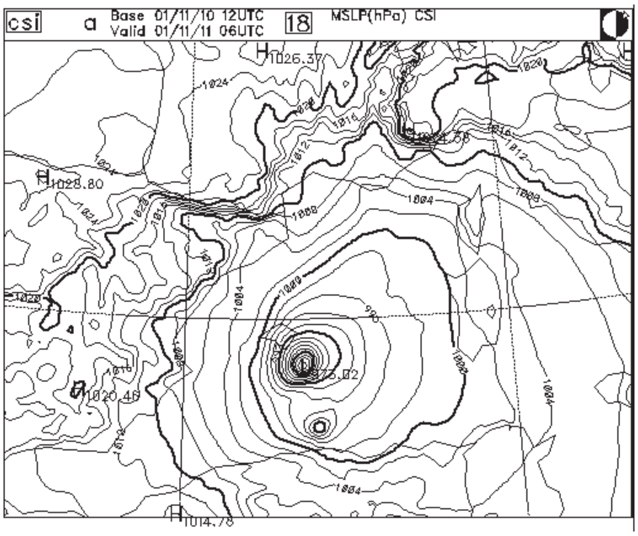

Figure 3a : 18-hour reference forecast of mean-sea-level pressure in the case study of the so-called Balearic "superstorm", based on 10.11.2001 12 UTC.

Figure 3b : The same, with activation of the conditional symmetric instability parameterisation inside the vertical diffusion scheme.

The introduction of the indirect representation of conditional symmetric instability (based on formulas 5 and 6) was tested mostly on the cases with rapid cyclogenesis (as the case of the "20 December 1998" cyclone). It seems that a linear dependency of the modified Richardson number on the original one is too weak to simulate turbulent processes connected to symmetric instability, that develop perhaps in a strongly nonlinear way.

To evaluate the global impact of the modifications based on the equations (2) and (4) budget calculations were provided on 96-hour runs of the ARPEGE model. For the scheme of the dry symmetric instability one can already see a not negligible change, mainly in the budget for temperature (Fig.4).

Apparently, the static stability at the top of the PBL is decreased mainly as a direct consequence of the changes in the vertical diffusion scheme.

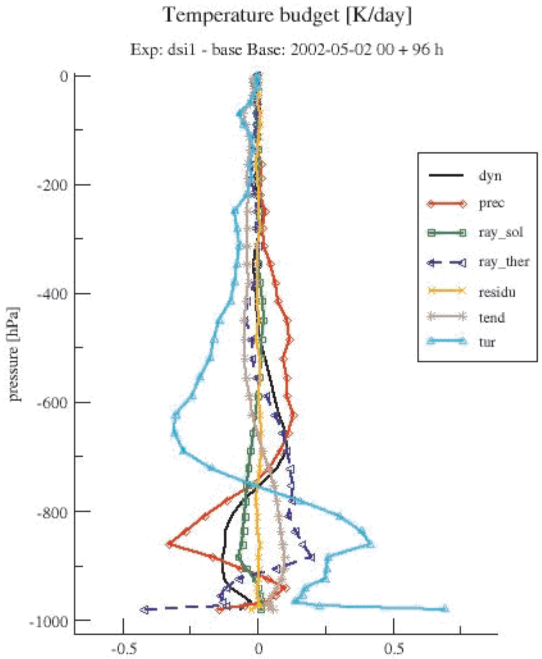

Fig.4 : Comparison of the global temperature budgets between the run with the parameterisation of dry symmetric instability and the run using the operational package of physical parameterisation (cycle 25T1_op4). Note the contribution of the turbulent fluxes (light blue line), the precipitation fluxes (prec) and the overall tendency (tend).

If we speak about considerable impact in the case of the dry symmetric instability, the parameterisation of conditional symmetric instability has already a global impact of unwanted dimensions (Fig.5). The tendency of warming the PBL and cooling the layers of mid- and upper troposphere by vertical diffusion is much bigger than in the previous case. For water-vapour budget there is a tendency to increase the transport of moisture from lower PBL levels upwards and to compensate it partially with the precipitation fluxes.

The activation of the shear-linked convection scheme has only a small influence on global temperature and water-vapour budgets, hence it is insufficient to compensate the large effect of a modified vertical diffusion scheme.

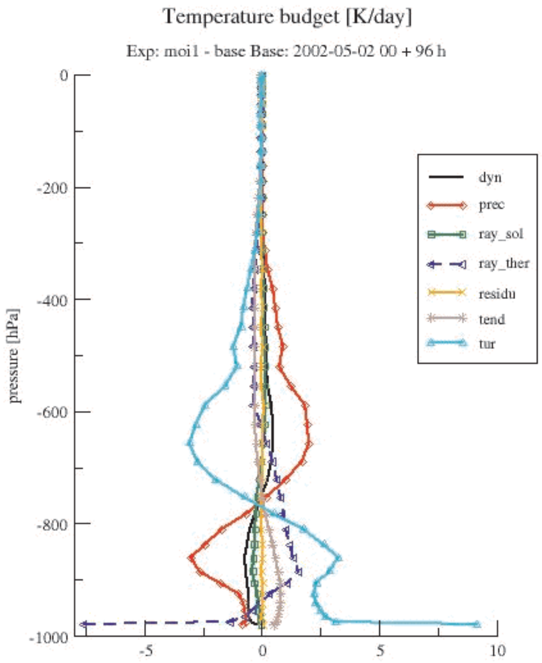

Fig.5 : Comparison of the global temperature budgets between the run with the parameterisation of conditional symmetric instability and the run using the operational package of physical parameterisation.

Conclusion

Results of the above-mentioned experiments tell us, that a decrease of stability in an environment with dry or conditional symmetric instability can be very important in the development of polar cyclones. However, the link between the conditional (dry) symmetric instability and cyclogenesis is most probably the same as it was discovered in the case of the "20 December 1998" cyclone, forecasted with the operational model scheme. Thus, cyclogenesis is generally enhanced due to large destruction of areas with high static stability in the planetary boundary layer. In contrary to the operational versions of ARPEGE/ALADIN, the vertical diffusion modified with respect to symmetric instability is more selective and dependent on the characteristics of the flow.

Nevertheless, it seems that the application of the scheme, as it was proposed using the equations (2) and (4), will not keep the desired equilibrium in the atmosphere. Adjustments of the Richardson number after equations (5) and (6) are not capable to haa ve significant impact on the selected cases because of their linear character.

Correct solution of the problem would require three conditions:

a) better diagnostics of the areas with conditional symmetric instability. The large global effect of modified vertical diffusion is most probably a consequence of overestimation of the conditions for symmetric instability by the model scheme.

b) understandings of the behaviour of turbulent processes in environment with slantwise ascent (descent). The turbulent transport in the case of symmetric instability reacts probably on the slantwise distribution of static stability and momentum. Hence it is not clear, if the turbulence propagating on a slope should be always treated in the same way as by neutral or unstable conditions. However, there is a lack of observations, that would confirm or refuse the hypothesis applied in (2) and (4).

c) redistribution of the fluxes on a slope, where the symmetric instability in the reality acts. It is possible that a slantwise turbulent transport doesn't lead to destruction of vertically stable layers, or at least not in such amount as by the pure vertical diffusion. A similar scheme of heat distribution resulting from slantwise convection was introduced by Nordeng (1987) and published in [5]. Nevertheless, in the current 1d physical parameterisation of the ARPEGE/ALADIN model it would be very difficult (if not impossible) to compute physical tendencies in a three dimensional frame.

All of these three tasks are not trivial and not promising automatically an improvement of forecasted cyclogenesis in the case of finding the proper solution. Hence the study will in the future evaluate also different possibilities how to support cyclogenesis and anticyclogenesis through the vertical diffusion scheme. A flow-dependent representation of mixing length could be an alternative topic for the research of the relationship between turbulent fluxes and cyclogenesis.

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